COMMUNICATIONS IN COMPUTATIONAL PHYSICS
Vol. **4**, No. 5, pp. 1258-1278

Commun. Comput. Phys.
November 2008

Simulation of High Power THz Emission from Laser Interaction with Tenuous Plasma and Gas Targets†

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Received 28 March 2008; Accepted (in revised version) 3 September 2008

Communicated by Zhihong Lin

Available online 9 September 2008

Abstract. With one- and two-dimensional particle-in-cell (PIC) codes, we simulate the generation of high power terahertz (THz) emission from the interaction of ultrashort intense lasers with tenuous plasma and gas targets. By driving high-amplitude electron plasma waves either with a laser wakefield or the beatwave of two laser pulses, powerful THz electromagnetic pulses can be produced by linear mode conversion in inhomogeneous plasma or by the transient current induced at the surfaces of a thin plasma layer of few plasma wavelengths. Even with incident lasers at moderate intensity such as $10^{17}W/cm^2$, the produced emission can be at the level of tens of MW in power and capable of affording field strengths of a few MV/cm, suitable for the studies of THz nonlinear physics. With field ionization included in the PIC codes, THz emission from laser interaction with tenuous gas targets is simulated. It is found that the transient transverse current formed during the ionization processes is responsible for the THz emission. With this mechanism, one may also obtain THz fields of MV/cm at lower laser intensity as compared with the schemes of plasma-wave excitation.

AMS subject classifications: 78A40, 78M25, 81V10

Key words: Particle-in-cell simulation, laser-plasma, electron plasma wave, high power THz emission.

†Dedicated to Professor Xiantu He on the occasion of his 70th birthday.
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1 Introduction

The recent development of laser technologies has enabled one to obtain ultrashort high power laser pulses with pulse duration ranging from few femtoseconds (or few cycles) to picosecond, peak power ranging from terawatt to the petawatt level, and focused intensity over $10^{20} W/cm^2$ [1]. The future development shall allow one to access even extreme laser conditions. Apparently such lasers provide countless possibilities of applications, such as laser fusion [2], creation of high energy density states [3, 4], advanced electron accelerators [5], energetic ion beams [6, 7], and novel radiation sources [8, 9]. For the last ones, currently the terahertz radiation (1THz=10^{12}Hz) from laser irradiated targets is attracting increasing interest. THz science and Technology become a frontier of research for intercrossing disciplines covering physics, chemistry, biology, materials science, and medicine now [10–13]. The THz radiation usually means the gap in the electromagnetic spectrum from 0.3 to 20 THz (1mm to $15\mu m$ in wavelength), which was not conventionally accessible either with optical methods or with electronical methods. However, the situation changes with the use of ultrashort laser pulses because their spectrum width (the inverse of the pulse duration) can be made in the THz regime. Currently based upon the optical schemes it is found that THz emission can be generated by optical rectification, optical conductive antenna, nonlinear difference frequency mixing, tunable parametric oscillators, optical Cherenkov radiation, etc. However, due to the damage limit of the optical materials, one cannot irradiate these optical materials with very high power lasers. With these schemes, it is thus difficult to obtain high power THz emission at the megawatt (MW) level. The latter is important for many applications and may allow one to study high-field and nonlinear physics in the THz regime in semiconductors, insulators, superconductors etc. [10] Currently MW narrow-band THz sources have been obtained from free electron lasers. Broad-band THz sources from ultrashort electron bunches either from linac and from laser wakefields are also suggested [14, 15].

On the other hand, plasma as a nonlinear optical media does not have a damage limit by high power lasers. Thus by irradiating plasma with such laser pulses, in principle one can obtain very high power THz pulses. Actually in 1990's, Hamster et al. observed experimentally THz emission by irradiating ultrashort laser pulses of 100 fs onto solid and gas targets [16]. Later THz emission from Cherenkov wakes in magnetized plasmas driven by ultrashort laser pulses was proposed [17, 18]. Recently, we suggested a new mechanism for THz emission based on the excitation of laser wakefields [19–23]. This emission is produced through linear mode conversion from a high-amplitude laser wakefield driven in inhomogeneous plasmas. This scheme can provide tens of megawatt (MW)-level emission with field amplitudes up to a few GV/m and still it allows for both compactness and relatively high efficiency by use of terawatt ultrashort laser pulses. Furthermore it is suggested that single-cycle THz emission can be produced with thin underdense plasma layers of few THz wavelengths in thickness irradiated by laser pulses [24].

In addition, ionizing gas targets are also potentially high power THz sources when irradiated by laser pulses at moderate intensities such as $10^{15-16} W/cm^2$ [25–31]. It is found